SCIENTIFIC BASIS FOR DRAINWATER USE FOR IRRIGATION

Introduction

Nature is controlled by inviolable, chemical, physical and biological laws. Advances in technology have resulted from research designed to discover these laws and then applying these laws to achieve the desired result. However, natural systems such as agricultural production include a vast array of physical, chemical and biological laws which interact in a very complex manner which are difficult to define and describe. Therefore, precise prescription for management to achieve a specific goal is difficult. Nevertheless, the probabilities of success in prescribing the best management operations are increased by applying the best scientific knowledge.

One major goal of our contract was to compile a comprehensive summary of research and demonstration projects that have been conducted during the last 20 years on use of saline drainage water for irrigation of agronomic crops as well as salt tolerant crops in the western San Joaquin Valley. In principle, the purpose of a demonstration project is to demonstrate the application of basic scientific knowledge in a practical field situation. A successful demonstration project is defined as one in which the results are consistent with the projected results based upon scientific knowledge. If the behavior of a demonstration project differs from the projected results, it implies that the basic scientific laws were not completely understood as they were applied to the system under consideration. A demonstration project from which the results differ from expectation may have the value of identifying shortcomings of the scientific understanding.

The purpose of this section of our report is to summarize some of the basic principles that should have application for agricultural drainage water use. This section is presented first so that it can serve as a basis for discussing the results from the demonstration projects which will be reported later in the report.

General Principles

All irrigation waters have some level of dissolved salts. Irrigation water is applied to soils from which pure water is released to the atmosphere through transpiration and/or evaporation. Thus, salts tend to concentrate in the root zone. Increasing salt concentration in the root zone will eventually decrease plant growth. Different crops have different degrees of tolerance to salinity in the root zone and therefore the level of salinity that can be accommodated in the root zone without yield reduction is crop specific. Nevertheless, there is an upper limit that can be accommodated by any plant.

Maas and Hoffman (1977) reviewed published research results of studies designed to compare plant growth to root zone salinity. They found that the data could be represented by curves such as depicted in figure 1. Growth is not reduced until a critical (threshold) salinity is reached and then the yield declines linearly with increasing salinity. The response is characterized by two coefficients: the threshold salinity and the slope of the lines for salinities greater than the threshold value. These coefficients are commonly referred to as the Maas and Hoffman Coefficients. Values of these coefficients for several crops can be found in various publications such as Maas and Grattan (1999). The more salt tolerant crops have higher threshold values. The slope of the declining curve is not necessarily reflective of the threshold value. A low slope identifies a crop that has relatively low decrease in yield as the salinity increases beyond the threshold value.

The salt concentration in the root zone can be controlled by occasionally applying more water than can be stored in the root zone and thus leach salts downward below the roots. Ideally, the amount of water applied for leaching purposes should be kept at a minimum because plant nutrients, particularly nitrates, are also leached from the roots along with the salts. Also high levels of leaching causes the water table to rise more rapidly and causing more drainage water in areas where subsurface drainage systems have been installed.

The optimal amount of applied irrigation water depends upon the salinity of the irrigation water, plant tolerance to salinity and the evapotranspiration (ET) of the crop. Although it is obvious that the amount of water required for leaching increases as the salinity of irrigation water increases, or as the plant tolerance for salinity decreases, the quantitative prescription of irrigation management cannot be established from this general understanding.

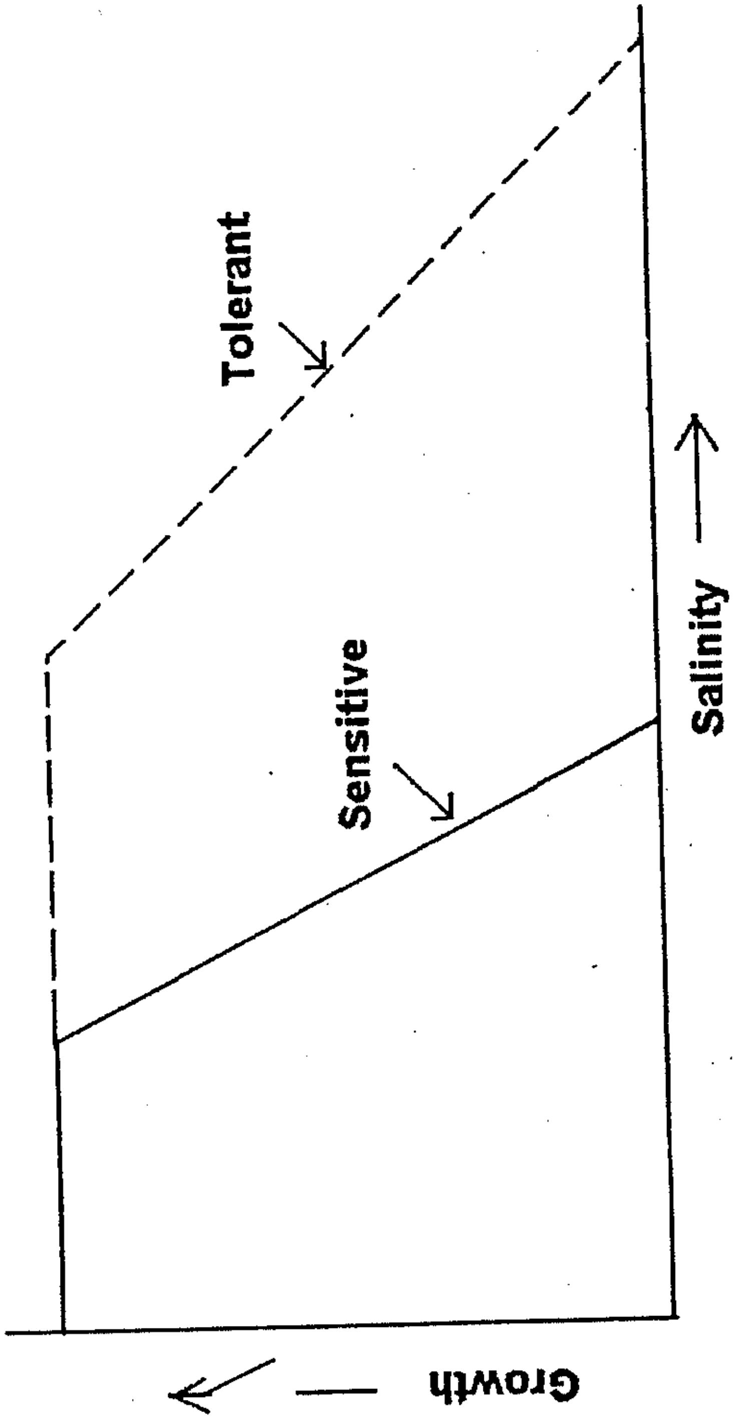

Figure 1. Generalized relationship between growth and average root zone salinity for salt-sensitive and salt-tolerant plants

One research approach is to conduct field experiments in which variable water application rates of different irrigation water salinities are applied and the yields are measured. However, several variables must be evaluated such as the amount of water applied, the salinity of the irrigation water, plant tolerance to salinity and the evapotranspiration rate. These variables make a complete field experiment almost impossible. As a result, most field experiments have been designed to investigate the effects of only one, or at most two, variables at one time.

Another approach is to develop models that appropriately combine all of the physical, chemical and biological laws applicable to the system in a manner to simulate the consequences of the various management options. A reliable model has the advantage of simulating the consequences of numerous management options in a short time which would take years and a huge budget to accomplish through field experimentation. Nevertheless the output from all models must be consistent with field observations and to the extent possible, quantitatively compared with field experiments, before they can reliably be used.

The next section reports the development and validation of a model. Later in the report, the model will be utilized to develop some basic principles involved with drainage water use.

Model Development

The model presented here is one component of the ENVIRO-GRO model (Pang and Letey, 1998). A basic component of the model is an equation describing the water flow through soil. The general water flow is described by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - A(z,t) \qquad [1]$$

where θ is the volumetric water content, t is time, z is depth, K (θ) is hydraulic conductivity, H is soil hydraulic head, and A (z,t) is a plant root extraction term. The first term ($\partial\theta/\partial t$) represents the rate of change of water content at a particular depth. The change in water content is dependent upon (1) the rate of water flow in and out of volume as described by the first term on the right hand of the equation, minus (2) the amount of water removed from the soil through root extraction and transferred to the leaf surface where it is transpired.

Salts in the water are considered to be conservative with no dissolution, precipitation, or plant uptake. Movement of salts is governed by the well-established convection-dispersion equation.

$$\frac{\partial(\theta C_s)}{\partial t} = \frac{\partial}{\partial z}\left[D_s(\theta,v)\frac{\partial C_s}{\partial z} - vC_s\right] \qquad [2]$$

Where C_s is salt concentration, v is the pore water velocity, and D_s is a combined diffusion and hydrodynamic dispersion coefficient of salt. The equation basically specifies that the change in concentration with time and any position is dependent upon the transport of salt with the flowing water and the movement of the salt by diffusion. The combination of equations of 1 and 2 describe the water and salt flow whereby the water and salt distribution in the root zone are computed.

The plant root extraction term (A) is what connects the plant to the soil system. The water uptake function is defined as:

$$\mathbf{A(z,t) = T_p(t)\Gamma\ (z,t)\sigma(h,\pi)} \qquad [3]$$

Where T_p is the potential transpiration rate, Γ is a plant root distribution function, σ is a crop matric potential-salinity stress function, h is soil matric potential (related to soil dryness), and π is soil osmotic potential related to salt concentration. The terms in parenthesis merely identify that the value of the main variable is dependent upon the values identified in the parentheses. For example, A(z, t) identifies that the water uptake from the root may differ at different depths (z) and at different times (t).

The potential transpiration rate (T_p) is defined as the transpiration that would occur if the plant was not under stress from deficient water or excessive salinity. It is readily recognized that the transpiration of a crop, such as cotton, will change as the plant changes in size and maturity. The common procedure that has been adopted to quantify crop water use is to multiply the potential transpiration that is demanded from climatic conditions (T_c) times an empirically determined crop coefficient (K_c) which changes with time to account from canopy coverage or different stages of crop development. Thus T_p in equation 3 is substituted by the commonly recognized variables ($T_c\ K_c$).

The root distribution (Γ), must be specified by the user. In otherwords, there is nothing in the model which prescribes the rate at which roots will grow. The user must have an understanding of the typical rate of root growth and distribution of roots in the soil profile and program that into the model.

The third term in equation 3, identifies how the soil matric potential (h, related to soil dryness) and π (osmotic potential which is related to the salt concentration in the root zone) affect the water uptake by the plant. This term is defined as:

$$\sigma\ (z,t) = \frac{1}{1+\left[\frac{\beta h\ (z,t) + \pi(z,t)}{\pi 50}\right]^3} \qquad [4]$$

where β accounts for the differential response of the crop to the matric and osmotic influences and is equal to the ratio of π_{50} and h_{50}; where h_{50} and π_{50} are the values of h and π at which the maximum transpiration is reduced by 50 percent. Note that when h and π equal zero, Γ in equation 4 becomes equal to 1. The placement of a value of 1 for σ

in equation 2 specifies that the plant water uptake will be equal to the potential transpiration without any reduction due to stress.

Equation 4 specifies that any value of h and/or π greater than 0 creates stress which results in σ having a value less than 1. This result is inconsistent with the well-recognized fact that plant growth is not reduced until the soil dryness or salinity level reaches a critical stage after which growth is reduced. Thus, the model was programmed in a manner (that will not be described here) to incorporate values of h_t and π_t which are the threshold values.

It is recognized that if part of the root system has adequate water and another part of the root system in stressed that the plant will compensate for the stress by taking more water from the zone in which water is not limiting. Thus, the model was programmed such that water to meet the transpiration demand was taken up from root zones with adequate water until the entire root system had combined matric potential and salinity levels above threshold values.

Thus far, the model has not been linked with plant growth. The total transpiration is the summation of the sink term (A) over time and depth and is related to crop dry matter production in a linear relationship:

$$\mathbf{RY = RT} \qquad [5]$$

Where RY is yield relative to yield under nonstress conditions and RT is water uptake relative to potential transpiration under nonstressed conditions. A linear relationship between dry matter production and transpiration as expressed in equation 5 has been documented in many research studies. Marketable yields are of primary concern to growers. For crops that have a linear relationship between dry matter production and marketable yield, equation 5 is valid for computing relative marketable yield. If the relationship between dry matter and marketable yield is not linear than a relationship between the two yields must be known.

Because transpiration is related to plant size, another adjustment had to be made in the model. For a nonstressed plant, the potential transpiration was calculated to be equal to the climatic transpiration times a crop coefficient. However, the crop coefficients are empirically determined under nonstressed conditions. If the plant undergoes stress it will grow more slowly and the value of K_c must be adjusted accordingly. Thus the model is programmed for continual feedback whereby if there is stress on the plant due to salinity or dryness, then the value of the crop coefficient is adjusted to accommodate the reduced growth.

As previously stated, numerous experiments reveal that dry matter production and transpiration are linearly related. Although this fact is commonly recognized it is commonly overlooked in estimating transpiration in the field. Transpiration of a crop is usually computed only from the climatic condition and specific crop. Although these two variables primarily control transpiration, crop size can have a significant effect which has practical implications.

The general water balance equation is:

$$AW = ET + DP + \Delta S \qquad [6]$$

Where AW is the applied water that infiltrates the soil, ET is evapotranspiration, DP is deep percolation and ΔS is the change in soil-water storage. Over the long term ΔS goes to zero.

Any factor that reduces plant size also reduces ET, and the consequences is that DP increases for a given value of AW. Therefore DP will be greater than estimated if the effect of plant size is ignored. In a saline environment the following dynamic process is put in motion. Increased salinity $\longrightarrow$ decreased plant size $\longrightarrow$ decreased ET $\longrightarrow$ increased DP $\longrightarrow$ increased salt leaching $\longrightarrow$ less salt in the root zone. Thus nature has provided positive feedback systems which is a partially protective mechanism.

Although it is outside the scope of this report, this dynamic process has other implications on water quality. Consider the case of nitrogen. If nitrogen is deficient $\rightarrow$ Less plant growth $\rightarrow$ less ET $\rightarrow$ more DP $\rightarrow$ more nitrate leaching $\rightarrow$ less nitrogen in the root zone. In this case there is a negative feedback system. The net effect is that reducing nitrate leaching by reducing nitrogen application may not achieve the intended result.

Model Validation

Very few experiments have been conducted which have both variable water application and salinity of irrigation water. The most extensive study was conducted in Israel on corn. The experimental variables were four irrigation water salinities (ECi = 1.7, 4.0, 5.3, 7.9 dS/m) and four irrigation-timing intervals (3.5, 7, 14 and 21 days). The comparison between the predicted relative yield from the model and the measured relative yield from the experiment are presented in figure 2. Note that there was very good agreement between the model prediction and measured results over the entire range of crop yield. This result suggests that the model can be used with confidence in simulating the consequences of irrigation and salinity management on crop yield.

Generalized relationships between yield, salinity, and applied water

Examples of simulated relative yield of a salt-sensitive crop (corn) and a salt-tolerant crop (cotton) as affected by the salinity of the irrigation water and the amount of water application is depicted in figure 3. The number on each curve represents the electrical conductivity in dS/m of the irrigation water. The horizontal scale represents the applied irrigation water divided by the pan-evaporation to standardize the curves for different climatic conditions.

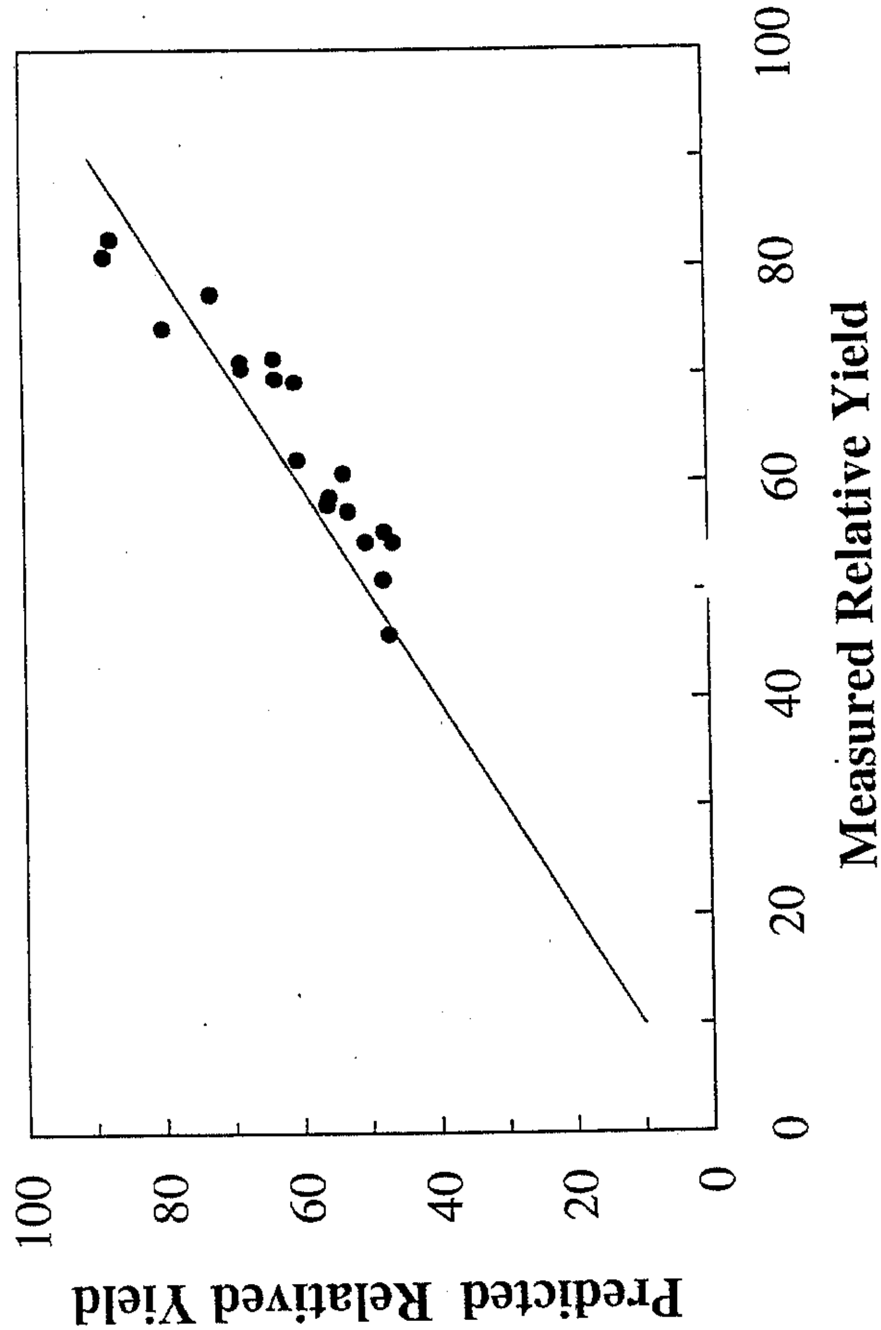

Figure 2. Comparison between predicted relative yield of corn from model simulation to experimentally measured results

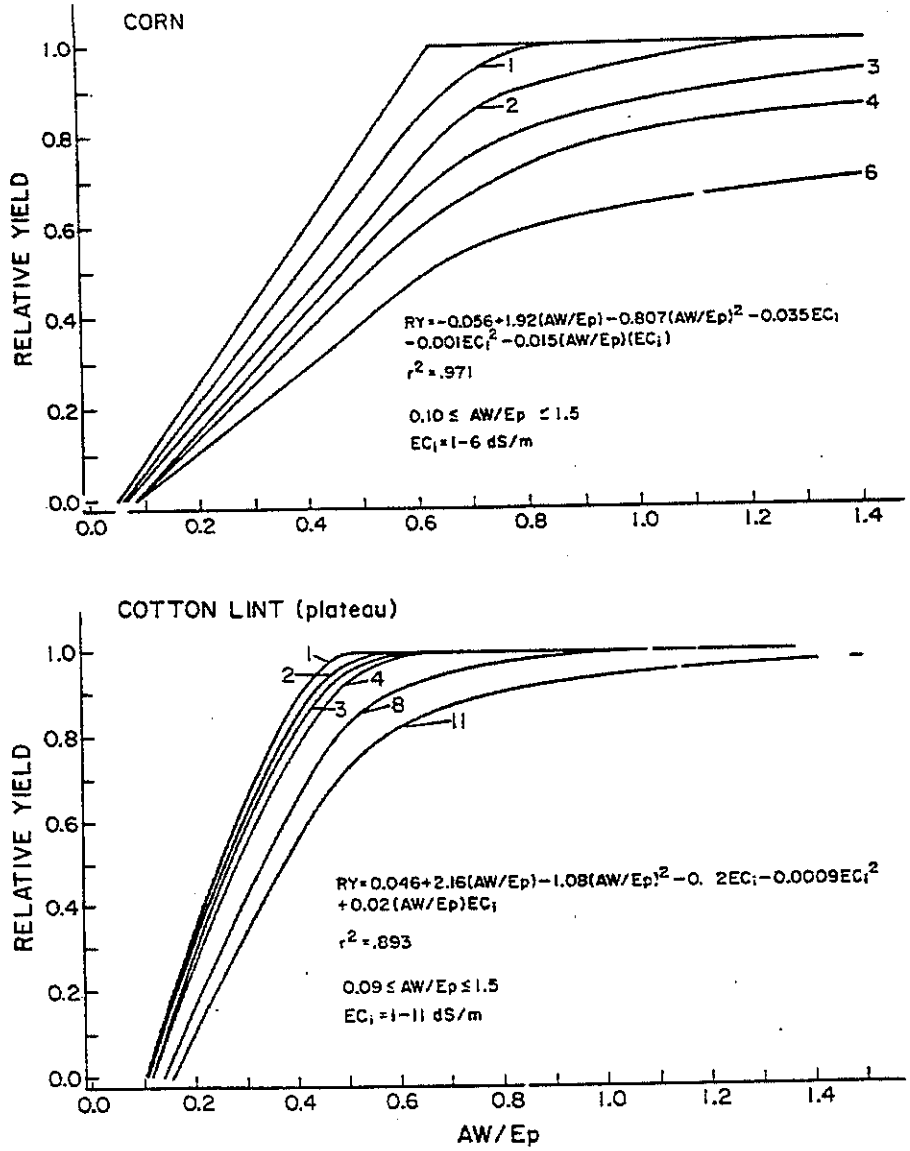

Figure 3. Relationships between yield and applied water for waters of different salinities. Numbers on curves refer to EC of irrigation water; AW and Ep represent applied water and pan evaporation.

Note that for a given water application, the crop yield decreases with increasing salinity. Also for a given salinity level the crop yield increases with increasing water application which contributes to leaching of salts. Note that for corn, relatively large decreases in yield occur with increasing irrigation water salinity. Maximum yield cannot be achieved irrigating with waters greater than 2 dS/m. Indeed, reaching maximum crop yield irrigating with a water of 2 dS/m would require a tremendously high water application that would not be feasible in the field. The results for corn depicted in figure 3 are generally consistent with the results from the field experiment in Israel depicted in figure 2. The lowest irrigation salinity used in the experiment was 1.7 dS/m. Based on figure 3 a relative yield between about .8 and .9 would be predicted depending somewhat on the amount of water application. Note that in figure 2 the maximum yield achieved in the experiment with the lowest saline water was in the .8 to .9 range.

In contrast to corn, relatively small decreases in cotton yield result from increasing irrigation water salinity, or relatively small amounts of higher salinity water needs to be applied to achieve the maximum yield. An irrigation water with a salinity as high as 8 dS/m could be used to grow cotton with relatively small decrease in yield.

These curves could be generated for any crop for which the salt tolerance (Maas and Hoffman) coefficients have been determined.

Generalized Drainage Theory

When the water table approaches the soil surface, a subsurface drainage system must be installed to prevent water logging of the root zone. A generalized depiction of the water table height at different times in relationship to the tile spacing is depicted in figure 4. Note that the scale is not the same in both directions. The depth of the drain may be 6 feet and the spacing between the drains are in 100s of feet. The main points to be made are that the drop in water table is more rapid over the drain and decreases with increasing distance from the drain line. Therefore, there will be more leaching immediately over the drain lines which decreases when moving away from the drain lines. The depth and spacing of the drain lines influence the dynamic behavior of the water table. The draw down of the water table will be more rapid with closer tile spacing and more rapid with deeper tile depth. No flow into the drain line will occur if the water table is not higher than the drain depth.

The path that the water travels toward the drain line is depicted in figure 5. This figure is taken from Jury (1975) who discussed the travel time of chemicals to subsurface drainage outlets. The horizontal axis represents a scaled distance from the drainage line. S equals half of the drain line spacing. For drain lines spaced 200 feet apart, S would equal 100 feet and the point on the graph identified as 0.9 would represent 90 feet from the drain line for this case. The vertical axis represents a scaled depth. For the 200 foot tile spacing a value of 0.5 on the vertical scale would be 50 feet. The graph represents an idealized case for a homogeneous soil system. In reality the actual curves could be somewhat different, but the main concepts that will be discussed later still apply.

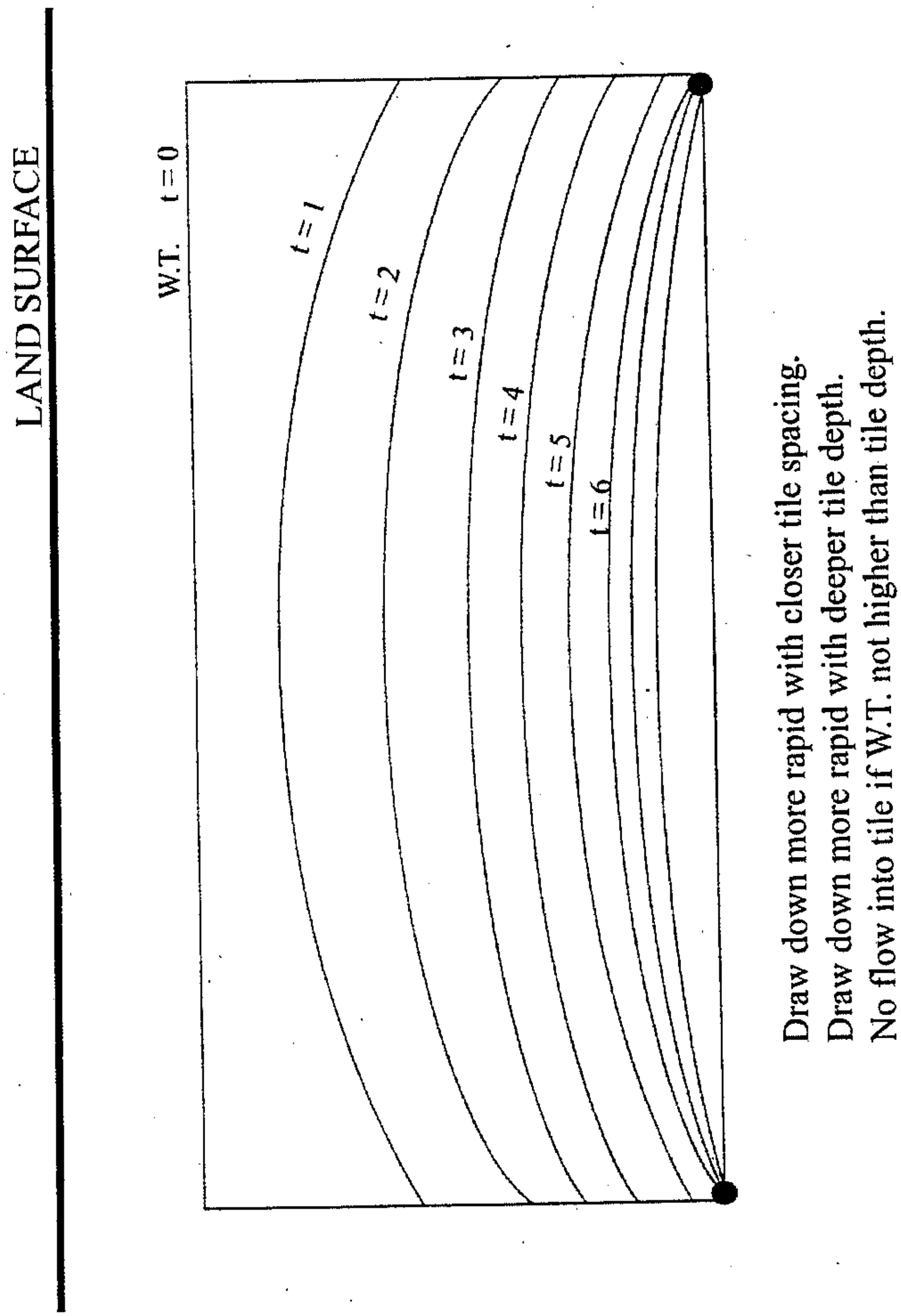

Figure 4. The general shape of the water table between tile lines for increasing time of drainage

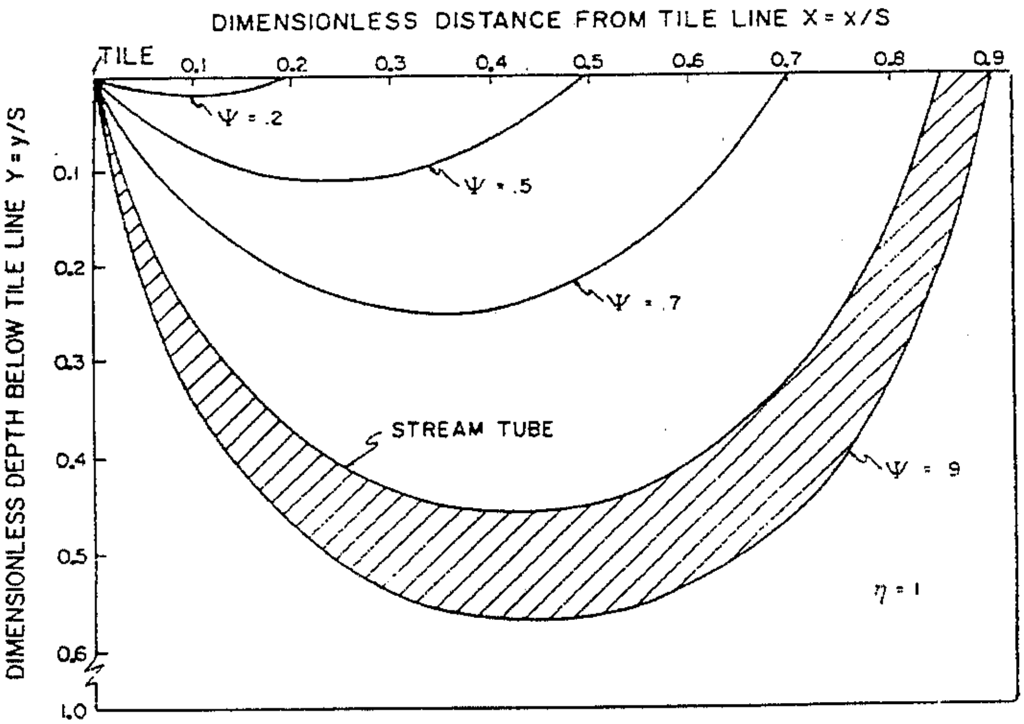

Figure 5. Streamlines followed by water flowing in steady state to the tile line. Shaded area shows path followed by water injected between X = 0.85 and X = 0.90.

The model presented above can be used to compute the amount of water and the salt concentration of water moving below the root zone. The water leaving the root zone must traverse a path as depicted in figure 5 before it reaches the drain line. Leachate immediately above the drain line goes directly to the drain. However, the leachate midpoint between the drain lines must travel hundreds of feet before it reaches the drain line. Thus, chemicals leaving the root zone midpoint between the drain line may not be collected in the drain line until decades later. The chemical composition of the drainage water is an accumulation of waters received from different parts of the field generated at different times. The chemical composition of the drainage water will largely reflect the composition of the shallow groundwater. However, the term "shallow" could include depths of tens of feet.

This information has significant implications to the sequential reuse concept for managing agricultural drainage waters. The concept as typically presented reflects the concentration of the drainage water from a field to be equal to the expected drainage water leaving the root zone. This will not be the case. This point will be amplified again when evaluating the sequential reuse concept.

General Hydrology

The land surface slopes upward moving west from the trough in the valley. A very low permeable 20 to 120 feet thick clay layer exists between 400 and 900 feet below the land surface and is commonly referred to as the Corcoran clay layer. The Corcoran clay layer separates a confined aquifer beneath it from the unconfined aquifer which resides above the layer.

Prior to receiving surface water supplies, irrigation water was derived from groundwater pumpage. From the period between about 1950 and 1965 approximately 100 million acre feet of water were pumped annually. After surface water supplies became available in the late 1960s, groundwater pumpage was greatly reduced and most of the irrigation water was from surface supplies. The amount of water irrigated each year from the surface supplies exceeded the amount when water pumpage was the only supply. The irrigation supply exceeded crop evapotranspiration and the water leaving the root zone migrated downward and caused the water table to rise. As the water table approached the land surface, it became obvious that a drainage system would be required. The depth of the water table, relative to land surface is smallest nearest the trough and tends to increase moving in a westward direction. However, because the land surface also increases, the actual elevation of the water table gradually increases going from the trough to the westward direction until a point is reached where the water table elevation decreases moving further west.

Letey and Oster (1993) used data reported by the Westlands Water District on the area of water tables at various depths for the period between 1967 and 1982. Based on these data, the average rise in water table between 1967 and 1976 was 0.58 ft/yr. The computed rate increased to 0.66 ft/yr between 1976 and 1982. For comparison, data collected from piezometers at the UC Westside Field Station was used to compute that the average water table rise was 0.66 ft/yr between 1962 and 1986 and 0.88 ft/yr between 1970 and 1986. Computations using data from USBR wells on Stone Land Company between 1975 and 1986 resulted in a water table rise of 0.80 ft/yr. Thus the calculated rates of rise were fairly consistent from the different sources of information.

A key question is, how much decrease in deep percolation below the root zone would.be necessary to arrest the rise of water table. The rate of water table rise can be computed from:

$$\textbf{W.T. Rise} = (DP \pm F_{lat} - F_c)/S \qquad [7]$$

Where DP represents the deep percolation, F_{lat} is the net lateral flow into the area. F_c is leakage through the Corcoran clay layer and S is the specific yield. The specific yield is related to how much water is required to raise the water table a given depth, considering the fact that part of the space is filled with solids and the other is already partially filled with water.

Assuming S to equal 0.1 and using the rate of water table rise ranging between 0.58 and 0.88 ft/yr as reported above, results in:

$$DP \pm F_{lat} - F_c = .058 \text{ to } .088 \text{ ft/yr} \qquad [8]$$

The result is that if the lateral flow and flow through the Corcoran clay layer remain constant a very small decrease in deep percolation would arrest the rate of water table rise.

However, after the drainage system was installed in Westlands, the amount of water collected in the drainage system was approximately 0.68 ft/yr. This is approximately 10 times the amount expected based on equation 7.

Various factors could have contributed to collecting more drainage water than would be anticipated based upon the rate of water table rise prior to installation of the drainage system. One explanation is that the farmers changed irrigation to create more deep percolation. However, there is no evidence that the farmers significantly altered their irrigation practices from times when the water table was quite deep until the time when they installed the drainage system. The other possibilities are increases in the lateral flow and/or decrease in the flow in the Corcoran clay. Both of these are probable. The drainage system would intercept much of the water that moved downward through the Corcoran clay. Also, as depicted in figure 5, the flow lines extend quite deep below the water table depth and rise up to the drain line. This could increase the hydraulic head gradient from the up slope area and increase the lateral flow.

These factors have significance on the advisability of using control on drainage line outlet to reduce drainage volumes which will be discussed in a later section of this report.

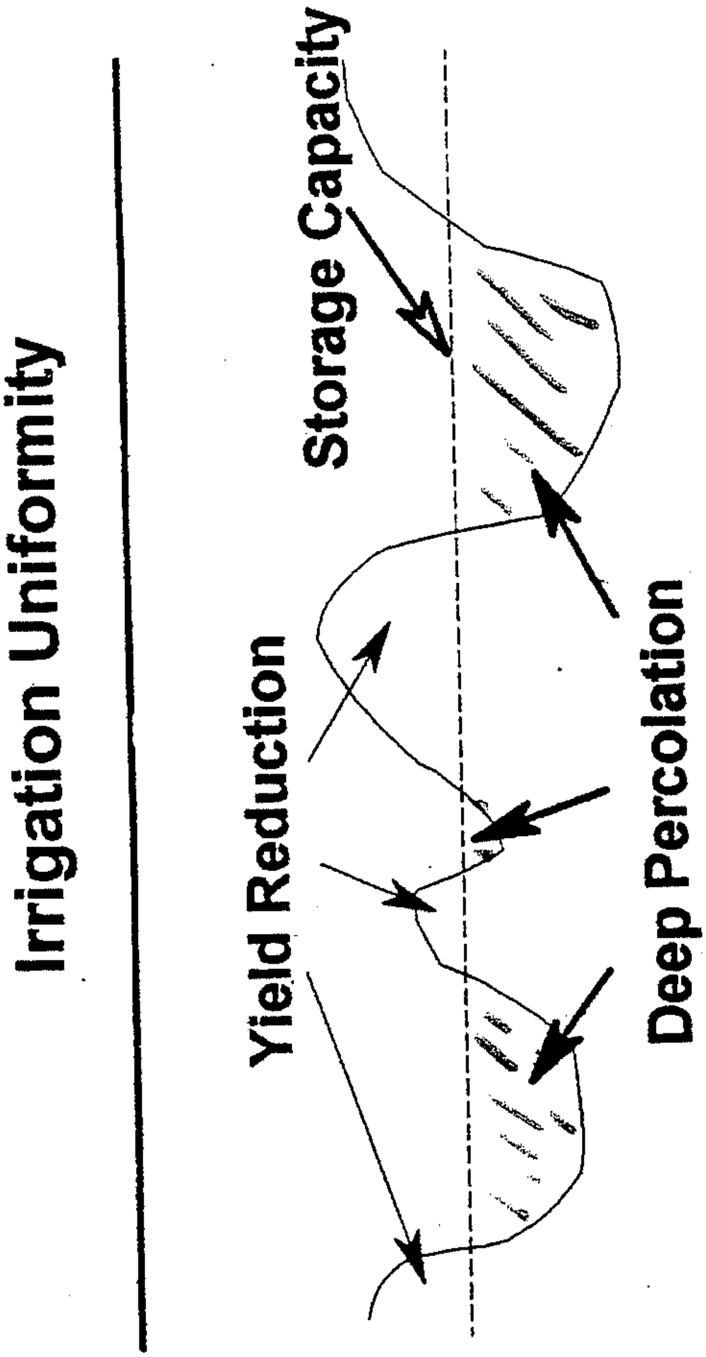

Figure 6. Illustration of the opportunity for both deep percolation and deficit water for crop yield when irrigation is not uniform

Irrigation Control

Reducing the amount of drainage water by reducing irrigation is a well-recognized strategy. However, evaluation of the irrigation management strategy is more complex than simply reducing the amount of water that is applied. The uniformity of irrigation is equally, if not more important, than the amount of water in dictating drainage volumes. A uniform irrigation would be defined as equal amounts of water entering the soil at all parts of the field.

Figure 6 illustrates the consequences of nonuniform irrigation. The ideal irrigation would be to recharge the storage capacity to replace water extracted by the crop between the irrigation events. Even though one targets a recharge of the storage capacity, if the irrigation is nonuniform, the storage capacity will be exceeded in some parts of the field and not filled in other parts of the field. The result is deep percolation in some parts of the field, and yield reduction because of deficit water on other parts of the field. The effect of nonuniform irrigation is two-fold -- yield reduction and high drainage.

Irrigation systems can be classified into pressurized and nonpressurized systems. A pressurized irrigation system is one where the water is delivered through pipes under pressure and discharged through various types of orifices such as sprinklers or drip emitters. A nonpressurized system would be the release of water and allowing gravity flow to move the water across the field such as in a furrow or border system. Pressurized systems allow accurate control over the amount of water applied because it is controlled by a valve. Surface irrigation systems allow less control over the amount of applied water because water has to be applied sufficiently to flow across the entire field. Applications of small amounts of water per irrigation event is not generally possible with surface systems.

There are two sources of nonuniformity associated with surface irrigation system. These are depicted in figure 7. One source of nonuniformity is referred to as opportunity time. Since water is on the upper end of the field longer than at the lower end of the field, more water would have the opportunity to infiltrate at the upper end as compared to the lower end of the field. A second source of variability is variability in soil properties which affect infiltration rates. The penetration of water is dependent upon the infiltration rate of the soil and this can be highly variable across the field. Thus, there is a combination of opportunity and soil variability which can influence the uniformity of application.

The uniformity of pressurized systems is controlled by the design and proper maintenance of the system. However, sprinkler system uniformity can be greatly affected by wind patterns. On the other hand, microirrigation systems such as drip can be uniform based on the appropriate design.

In principle, the microirrigation systems are "best" because they allow precise control over the amount of water applied and if properly designed and maintained can deliver the water very uniformly. The sprinkler system has the advantage of having control over the amount of water applied but the uniformity of application is dictated by wind conditions. Surface irrigation systems allow the least control over the amount of water application

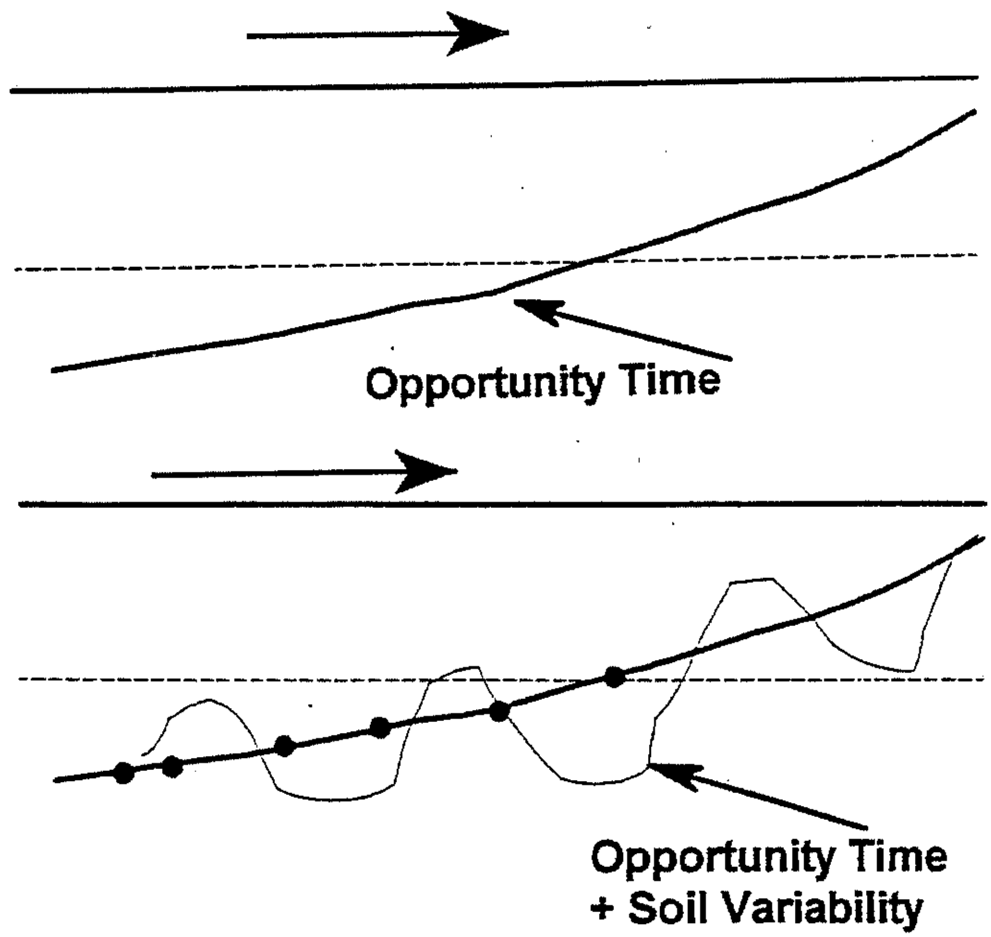

Figure 7. Illustration of depth of water penetration as water flows down a furrow from left to right. Upper curve is for soil with uniform infiltration rate and lower curve is for soil with variable infiltration rate.

and uniformity of irrigation. However, the costs for these systems are directly related to their potential benefits. Therefore, the economically optimal irrigation system is not always obvious. Indeed, a study by Letey et al. (1990) concluded that if there is no cost for drainage water disposal, surface irrigation systems would be more economical than the pressurized systems. However, if there were considerable costs associated with drainage volumes then the economically optimal system shifted to pressurized systems.

Reports have been made that a surface irrigation system can be properly managed to have uniformity almost equal to the pressurized systems. These statements are based upon numerical uniformity values for the different systems. Which raises the question, how is uniformity measured? For surface systems, the rate of advance of water down the furrow is measured and these numbers are inserted into equations developed to compute the nonuniformity associated with opportunity time. These measurements do not include the nonuniformity associated with soil variability, which can be considerable. Therefore the numerical values for furrow systems are over-estimates of the true uniformity. Uniformity of sprinkler systems is measured by distributing containers in a collection area and measuring the amount of water collected in each container. The numerical result is dependent upon the size of the container. Using larger containers, will result in a higher uniformity value than using smaller containers. Thus, the number is already recognized as being somewhat subjective, based upon the measuring technique. Even a drip system is very nonuniform if the measurement is made on a very small scale. The water released at the emitter is very high and the water between emitters is very low. Nevertheless, a plant root system can integrate differences in water in different parts of the root zone and even things out.

A few facts become evident. Meaningful measurement of uniformity is difficult. For one thing the size of the root system must be considered from a practical point of view. A tree with a large root system can accommodate considerable nonuniformity of water application under the canopy. Whereas a shallow-rooted vegetable crop would be greatly impacted by the same distribution. It is also evident that the numerical values from the surface systems are over estimates of uniformity whereas the numerical measurements on the pressurized systems are designed to give rather low uniformity numbers.

These comments should not be interpreted as being critical of the mobile labs used to measure the uniformity of irrigation systems. These analyses can be very useful in comparing one surface irrigation system against another surface irrigation system and they are useful in helping to design management strategies to improve the uniformity of these systems. The main point to be emphasized is that measured uniformity values for different irrigation technologies cannot be quantitatively compared. Thus, any report that compares the uniformity of different irrigation technologies by numerical values cannot be accepted as being quantitatively valid.

Drain Outlet Control

Drainage flows can be controlled through irrigation management. Potentially, very low drainage volumes could be achieved with a properly designed and maintained drip irrigation system. However, surface irrigation is likely to be used a very high percentage of the time because of the cost. Control over the drain line outlet provides an additional opportunity for reducing drainage volumes. Most drain lines are installed at depths of six or greater feet. The water table can be higher than that depth without detrimental effects on crop production.

The benefit of controlling drainage outlet has generally been considered from the point of view of retaining water in the profile allowing the plants to extract water from the saturated zone. In other words, water that would normally flow out the drain line is retained in the profile and made available for the plant. This results in a savings of irrigation water as well as a reduction in drainage volumes.

Each irrigation with good quality water moves the salts that have concentrated in the root zone downward towards the bottom of the root zone. This process maintains the upper profile relatively free of salts allowing the roots to proliferate in that zone and extract the required water. Plants generally have the ability to extract extra water from sections of the root zone with adequate water to compensate for reduced uptake from saline portions of the root zone.

Controlling the drainage line outlet may have other benefits in addition to retaining water for plant use. Another section of this report identified that the amount of water causing the rate of water table rise before drainage systems were installed was considerably less than was collected in the drain lines after the system was in place. It was hypothesized that installing the drainage line intercepted some water that previously was leaking through the Corcoran clay and also possibly creating hydraulic gradients increasing lateral upslope flow. Closing the drains is the same as not having the drains installed and the hydraulic gradients adjust accordingly. Thus, in addition to retaining water in the profile for the plant growth, two additional potential benefits are inducing more water leakage through the Corcoran clay and reducing lateral flows from upslope areas.

The consequences of nonuniform irrigation may be partially mitigated by drainage control. Nonuniform irrigation at the surface conceivably could be partially offset by lateral flow created by differential hydraulic head gradients within the field from areas where the infiltration rate is high to the area where the infiltration rate is low.

Storage of water is one other potential benefit of drainage outlet control. As previously stated, the water table can be maintained at a depth higher than the drain line depth. This zone represents a storage capacity that is lost when the lines are allowed to flow freely and lower the water table to the tile line depth. There are examples for need of storage capacity. Total annual discharge of chemicals into the San Joaquin River can be increased by real time management. Real time management refers to the temporal discharge based upon the assimilative capacity of the river. The assimilative capacity of the river varies through the year. The typical drainage volumes may not coincide with the assimilative capacity on a temporal basis. Storage may be required. Storage within the profile is preferred to surface storage because it does not have environmental consequences.

Storage could be important is the use of evaporator ponds. The concept of evaporator ponds is to discharge water into the pond at the rate at which it evaporates, thus not creating any ponded water to attract birds. Again, the rate of evaporation varies throughout the year and is not coincident with the natural flows from drain lines. The opportunity to store in the profile and then discharge it at times when it could be evaporated without ponding in the evaporator pond is another potential benefit of drainage outlet control.

Much of what has been stated in this section about drain outlet control is, at this time, speculative. Nevertheless there is some scientific basis justifying the speculation. Research and demonstration projects to verify or refute the speculated benefits proposed in this section is a high priority. Some studies have been done on drainage release control with some derived benefits reported. However, the present studies are inadequate to address all the various issues that have been proposed here.

Drainage Reuse Strategies

Using drainage water for irrigation can serve two purposes – one is to dispose of drainage water that would otherwise be costly to dispose, the other is to use drainage water from the positive prospect of growing a crop for economic value. The latter approach has the added benefit of reducing the requirement for good quality irrigation water. In reality, these two purposes are complementary and the optimal choice is based on economics.

There are three basic choices for a farmer to manage both good quality and drainage water resources: (1) the waters can be mixed together to get a water with average salinity (blending strategy); (2) use different waters to grow crops with different sensitivity in a crop rotation on the same field (cyclic strategy); (3) select part of the farm to use good quality water to grow salt-sensitive crops and another part of the farm to use saline water and grow salt-tolerant crops.

Rhoades was one of the initial scientists to promote the merits of the cyclic as opposed to the blending strategy (Rhoades et al. 1992). The greatest benefit of using the cyclic rather than the blending strategy is that a combination of salt-sensitive as well as salt-tolerant crops can be grown. Blending might result in a average salinity that would be prohibitive for use in growing the more salt-sensitive crops. Bradford and Letey (1992) used model simulations to demonstrate the validity of cyclic versus blending strategy in growing both salt-tolerant (cotton) and salt-sensitive (corn) crops. In a crop rotation, using the same amount of saline and nonsaline water in blending and cyclic strategies, the cotton yields were the same for both strategies. However the corn yield was lower under the blending strategy as compared to the cyclic.

Bradford and Letey (1992) also reported that the same results could be achieved by the blending and cyclic strategies for a given crop. They selected a perennial alfalfa crop for the simulation and determined that the long-term average yield was the same whether the waters were blended or applied cyclically. One significant finding of the simulation, however was that by applying saline and nonsaline waters on alternate years, the lower yield resulted during the year when the nonsaline water was applied. This finding is significant because it illustrates the dynamic nature of salinity and crop management. When saline water was applied, the salinity builds up in the soil profile during the crop season and therefore the initial salinity was high the following year when good quality was applied. Good water quality leached the salts during the growing season so that on the next year when saline water was applied the profile was initially low in salinity. The result is that the salinity in the soil at the beginning of the crop season is very important. If the profile is free of salts, the effects of adding saline water may not be detected during the first year until the soil salinity is increased. Likewise, if the profile is salt-laden at the beginning of the season, this will have impact on the production even though nonsaline water is used during the growing season because there is a time delay before the soil becomes free of salts. The important point being is that salinity in the soil profile in the beginning of the growing season is very important and that there is a time delay between changing irrigation water quality and the build up or removal of salinity within the profile to which the plant will respond.

The third option of selecting a part of the field to use good water on salt-sensitive crops and another part of the farm to use saline water for growing salt-tolerant crops is conceptually the same as the cyclic strategy. The only difference being that the cyclic strategy implies using the same plot of land with the opportunity to have a crop rotation with salt-sensitive and salt-tolerant crops. The other option is simply to devote a given land area to either growing salt-sensitive or salt-tolerant crops. Segregating the farm into areas growing salt-sensitive and salt-tolerant crops entails less operational complications than the cyclic strategy on the same field. The cyclic strategy entails having a water delivery system for fresh and salt water. Whereas the segregated approach requires a less complex delivery system.

Thus far the blending concept has been discussed on the basis of blending all the water supplies. Dinar et al. (1986) computed optimal ratios of blending nonsaline water with saline water of different salinities for different crops. Except for the most sensitive crops and extremely high water salinity, some blending of the waters was optimal for many crops. Providing the optimal mix of fresh and saline waters for irrigating individual crops is probably not operationally feasible. However, it is important to recognize that drainage waters do have utility for growing economic crops. For example, note in figure 1 that irrigating cotton with an irrigation water of EC = 4dS/m is not much different than irrigating with water of 1 dS/m. Indeed, waters with as high as 8 dS/m can be used for growing cotton. Therefore using saline water for growing cotton is almost as efficient as using fresh water.

Soil Chemical Factors

The chemical composition of the irrigation water, fertilizer application and the presence of calcite and gypsum in a soil affect salt balance. The chemical composition of the aqueduct water is such that when applied to calcareous soils of the Westside San Joaquin Valley, it will dissolve calcite from the soil at leaching fractions exceeding about 0.17. At lower leaching fractions some of the calcium and bicarbonate contained in the irrigation water will tend to precipitate. The application of ammoniated forms of nitrogen fertilizer will tend to increase calcite dissolution, because the oxidation of ammonia to nitrate releases hydrogen which neutralizes a portion of the bicarbonate in irrigation water.

Some of the Westside San Joaquin Valley soils are also gypsiferous, i.e. in their native state they contained gypsum. This gypsum may still be present within and below the rootzone. The calcium and sulfate content of the aqueduct water is such that it will dissolve this gypsum as it moves through the rootzone. But when gypsum dissolves, Ca is released and it exchanges with adsorbed Na so that the soil water becomes a $Na\text{-}SO_4$ type water of high salinity, much greater than the solubility of gypsum, ECs in the range of 8 – 25 dS/m (Tanji et al., 1972). Leaching fractions would need to be very low, about 0.02, in order to prevent gypsum dissolution. How much dissolves depends upon the amount of exchangeable sodium and magnesium present in the soil. As this dissolution occurs, the drainage waters become enriched in sodium, magnesium and sulfate. If gypsum is present along the path along which irrigation water flows through the soil, its dissolution will act as a salt source until it is all dissolved. This could take a long time to occur. For gypsiferous soils irrigated with the aqueduct water available along the Westside San Joaquin Valley, gypsum dissolution will result in greater amounts of salt in the drainage water than in the irrigation water for a long time to come.

Soil Physical Properties

Thus far the discussion on using drainage waters for crop production has been on plant response. Another potential hazard of using drainage waters for irrigating crops is a deterioration of the soil physical properties through dispersion creating hard crusts and soils with very low infiltration rates. Indeed, the early field experiments on using saline water for growing cotton (Raines et al. 1987) was impacted by poor seed germination associated with deteriorated soil physical conditions when the higher salinity waters were used for irrigation. No efforts were made in that experiment to mitigate the effects of water quality on soil physical properties.

The sodium adsorption ratio (SAR) of the irrigation water is the critical parameter related to soil physical conditions. The SAR is related to the chemical composition of the water by:

$$\mathbf{SAR} = \frac{\mathbf{Na^+}}{\mathbf{[(Ca^{++} + Mg^{++})/2]^{1/2}}} \qquad [9]$$

Where the concentrations of sodium, calcium and magnesium are expressed in milliequivalents per liter. The monovalent sodium tends to cause soil dispersion, whereas the divalent cations tend to cause the soil to become flocculated. The detrimental effects of drainage water with high SAR on soil physical properties can be mitigated by adding a calcium source such as gypsum.

Actually, the high electrolyte concentration of saline waters prevents dispersion even for waters with high SAR values. The problem arises when the highly saline water is followed by good quality water, which then causes the dispersion. Therefore, the critical period for soil dispersion is during the rain period, when basically distilled water is added to the soil which can destroy the soil physical properties. Thus the timing of gypsum application is most efficient when applied to the surface prior to the rainy season. Guidelines are available for appropriate gypsum application to preserve soil physical properties. Those details will not be presented in this report.

Some uncertainty exists whether growing forages such as Bermuda grass with a very dense root system and with the soil land surface being completely covered can prevent the break down of soil physical conditions. Certainly these soils would be less susceptible to dispersion than bare soils often associated with other crops, particularly those that are cultivated or plowed before the rainy season. Additional studies are required to establish the extent to which soil physical properties will be preserved if forages are irrigated with drainage waters without the application of an amendment such as gypsum.